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UNITED STATES AIR FORCE

AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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THE HISTORY OF FALLOUT PREDICTION

REPORT

JAY C. WILLIS

Report on

6 THE HISTORY OF FALLOUT PREDICTION.

by

10 Jay C. Willis
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School of Engineering
Air Force Institute of Technology
Wright-Patterson Air Force Base OH

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Preface

This paper is the primary product of a special study course in nuclear weapons effects. I chose the subject of fallout modeling because I was interested in finding out where the fallout prediction systems I had been previously exposed to came from. As I began the effort, I was surprised both by the volume of material that had been printed on the subject and by the difficulties I encountered in trying to track down some of that material. So due to material left unstudied either because of its unavailability or because of time constraints, this paper presents far less than a definitive history of the science of fallout prediction. Hopefully, however, it will provide the reader some insight into the development of this discipline.

I wish to thank Dr. C. J. Bridgman for his invaluable guidance throughout the course. I also owe a special thanks to Dr. R. R. Rapp of the RAND Corporation and to LTC Philip J. Dolan (U.S. Army, retired) of SRI. Their views, gained by experience in the fallout business virtually from its beginning, were freely given and played a crucial role in cementing together an otherwise fragmented history.

Contents

Abstract

The development of the science of fallout prediction in this country from 1950 to 1979 is described. The chronological description emphasizes early developments and the relationships between some of the significant calculational models. The earliest work on fallout prediction discussed is that performed by RAND on Project Aureole in 1954, and the evolution is carried through to the derivatives of the DELFIC computer code. A section is devoted to the histories of four commonly used handbook prediction systems.

THE HISTORY OF FALLOUT PREDICTION

I. Introduction

Fallout is recognized today as an extremely lethal effect of nuclear weapons; it is presumed that the reader is aware of the scope of this phenomenon. The prediction of the extent of a fallout pattern can therefore impact greatly on the decisions made at all levels of government, from a head of state assessing strategic casualties to a troop unit commander in the field trying to decide where he may safely lead his men. Naturally, one would desire the predictions to be accurate.

Far from being an academic problem already solved in a closed form, fallout prediction is a science that has been in continual (though fitful) evolution since the early 1950's. And it is certain to continue to evolve for a time to come before there is any great satisfaction with prediction accuracy. In the past 29 years a vast amount of written material has been published in both the classified and open literature on the subject of fallout. This material describes dozens of systems that have been developed specifically to perform the predictions.

The purpose of this paper is to describe the development of fallout prediction systems in this country. The description, emphasizing early developments, is in terms of a chronology of major events and in terms of the relationships between some of the significant systems. A separate section will be devoted to the histories of four handbook systems currently in common use.

Several limitations in scope will be observed. Generally only systems which predict fallout primarily for land surface bursts will be considered. Emphasis will be given to fallout "models" that attempt to

mathematically describe in some degree the physical processes of fallout rather than to systems making predictions by means of comparison. (The handbook systems described in the last section will, of course, be an exception.) The references for the models discussed will usually be the documents describing in most detail the calculational model used for fallout prediction. Thus supplementary papers slightly modifying the basic model, comparing its results to test shots, or integrating the model into a practical casualty prediction system will be largely ignored.

As a caution to the reader, many prediction systems, including true models, will not be covered. An attempt was made to describe the models most significant in the development of the science; but it is quite possible, or perhaps probable, that some of the important works have been unjustly neglected.

II. Background

Following the operational explosions over Hiroshima and Nagasaki, the United States began peacetime testing of nuclear weapons. For various reasons, among them probably a lack of large quantities of fissionable material, there were only five such tests prior to 1951. They were all tower shots and, being such, did not result in what is variously called local, early, or militarily significant fallout.

In 1951, the U.S. began a more ambitious program of nuclear testing; one that would result in 135 atmospheric detonations by the end of 1958. A moratorium on all nuclear testing was observed by the U.S., U.S.S.R. and United Kingdom from November 1958 to September 1961, when the U.S.S.R. began an unannounced series of detonations. The United States then resumed its own testing at a pace quite accurately described as feverish. The tests were mostly underground, but they included some atmospheric detonations until the Limited Test Ban Treaty took effect in October 1963.

During all these tests - a total of 183 atmospheric tests by the U.S. alone - not one had been conducted for the primary purpose of observing fallout. Most tests were probably conducted simply to test a new weapon design, but many were also intended to measure nuclear effects other than fallout. In the 1950's, the effects of greatest interest were blast and thermal; later, x-rays, EMP (electromagnetic pulse), TREE (transient effects on electronics), and prompt radiations would seem important. Nevertheless, residual radiation always took a back seat.

The first two tests to yield significant local fallout occurred in 1951, but they apparently did little to alert the government to the fact that fallout could be a dominant casualty producing effect. With the initial tests of thermonuclear devices in the Pacific in 1952, and later in 1954, with two huge fallout patterns, interest began to stir. But never was a test shot made primarily for the benefit of those seeking to measure or model fallout.

Among the reasons for this was that, quite simply, to purposely produce the sort of fallout pattern the modelers would have wanted would have been very dangerous. The 1954 thermonuclear test had resulted in some rather embarrassing contamination, and thereafter such large yield tests were conducted only under specific meteorological conditions. These were such that the radioactive cloud rose and fell just as near to ground zero as possible. Thus the winds were low velocity and highly sheared with altitude - certainly not the ideal conditions under which to develop a fallout model. Testing on U.S. soil, besides using relatively low yield weapons, was designed to give very small fallout patterns for quite obvious reasons.

Even for those tests that did result in fallout, data was often incomplete and of poor quality. So very few shots yielded really useful data. The situation may be appreciated by the fact that the very first shot in 1951, the Sugar shot of the Buster-Jangle Series, that resulted in fallout remains probably the best documented of any such test. This is partially understood in light of the competition for resources and the furious pace of later testing. Fallout was only one of the less important competitors for finite amounts of manpower, equipment, and money. Tests also came so rapidly that preparations for experimental measurements were rushed, and analysis of data lagged significantly. For example, on some test shots several different types of radiation detectors were used because no one detector had been tested sufficiently to be fully trusted. Of course, this resulted in conflicting readings.

So the scientists charged with producing fallout models worked with a rather poor data base. Nonetheless, they were asked to develop models to predict fallout patterns from bursts well outside the realm of experience in terms of yield, soil, height of burst, and weather. Particularly serious was the gap in data for various yields. The tests resulting in fallout were generally either for yields of a few kilotons or several megatons. To make matters worse, the data was generally difficult to obtain. Naturally, it was all classified, but it was also not available from a single source until 1965.

A final obstacle faced by those who worked in fallout modeling was the fluctuations in interest in fallout (usually equating to money made available) by the government. Like an electronic servo system with poor feedback, the business had a lot of ups and downs. Government interest in fallout always followed the key event by a certain time; appropriations lagged behind the first interest; results naturally had to come only

after the money was appropriated; and by the time things got going, the money was likely to have shifted to other quarters. For these reasons, one must be extremely careful when attempting to identify cause/effect relationships; often the cause precedes the effect by a deceptively long time.

III. Chronology: 1950-1961

From nearly the beginning of the era of atomic weapons, it was recognized that residual radiation was a possible casualty producing agent. The concept of fallout indeed preceded the first atomic detonation to produce significant local fallout and is briefly described in the first unclassified authoritative text on nuclear weapons effects, The Effects of Atomic Weapons (Ref 13) published in August 1950. The text in fact discusses fallout particle formation and presents the basic equations for particle transport. But, as evidenced in part by the absence in the book of any practical method to predict even roughly the geographic extent or radiological dose rates that might be associated with fallout, there was little appreciation in 1950 that fallout could be an extremely potent (even the dominant) casualty producing effect of nuclear weapons.

It was not until 19 November 1951, that an atomic weapon detonation by the free world occurred close enough to the earth's surface to produce a significant quantity of local fallout. This test was the Sugar shot of the Buster-Jangle series in Nevada.[1] With a height of burst of four feet, the weapon had a yield of 1.2 kilotons. Ironically, this first

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[1] All information in this paper on specific weapons tests is taken either from Ref 7 or Ref 14:672.

surface burst was probably the best documented of all of the local fallout producing shots of the United States, for many years providing the real core of experimental data with which to design and test fallout models. But for some unknown reason, the shot apparently did not alone stimulate any real interest in the writing of systems with which to predict the extent of fallout.

The Mike shot of the Ivy series of Pacific tests appears to have stimulated the first organized interest in fallout (Ref 33). Mike was a 10.4 megaton weapon, the first thermonuclear device detonated by the U.S. Occurring on the Eniwetok atoll coral sand on 31 October 1952, the surface burst produced extensive local fallout. Unfortunately for the future model writers, as the fallout fell over water sparsely populated with monitoring stations, the shot was very poorly documented. But particularly due to the change in scale of yield (four orders of magnitude), the problem of fallout started to receive the active interest of the government.

This interest resulted in part in the assignment of the RAND Corporation to study fallout. In the summer of 1953, RAND held a fallout symposium of sorts to begin to study the phenomenon. The results of this activity were Project Sunshine, to investigate worldwide fallout, and the lesser known Project Aureole, to investigate local or close-in fallout. Project Sunshine was then viewed as the work of primary interest; but within the classified report of Project Aureole, published in July 1954 (Ref 16), was contained one of the first working fallout prediction systems - the so-called "first RAND model" (Ref 33). A copy of the Aureole report, R-265-AEC, still classified, was not available to this author, so little is known for certain of the model

it contains. However, if other RAND work published concurrently or the follow-on models are indicative, this first model was probably a disk-tosser using hand calculations.

Earlier in 1954, an event took place which dramatically stimulated yet more interest in local or militarily significant fallout. This was the Bravo shot of the Castle series of Pacific tests. Detonated on the surface at Bikini atoll on 28 February 1954, the 15 megaton device produced a fallout pattern much better defined than that observed at Ivy Mike. Due in part to unexpected meteorological conditions downwind, the pattern was surprisingly extensive, resulting in a Japanese fishing vessel in the area being seriously contaminated. This shot apparently stimulated more of an interest in fallout by the military than had Ivy Mike (Ref 11). (Another shot in the Castle series, Koon, on 6 May 1954, with a yield of 110 kilotons, was a surface burst. Although complaints were noted by this author in several places that a lack of data existed in this yield range, no reference to this burst has been found in the fallout model literature.)

In October 1954, Dishington of RAND published RM-1371 (Ref 9) entitled "A Model for Fallout Calculations." This model was not developed as part of the RAND work on Aureole (Ref 33); but it is the earliest model this author has reviewed. It probably reflects much of the substance of the data presented by the Aureole report and represents very clearly the conventional disk-tosser fallout model. Even in these early models, some essential features have appeared, including particle size/activity distributions, particle fall rates, activity distribution in the cloud, wafers described by altitude and particle size ranges, and $t^{-1.2}$ decay of activity. The

data base of the model is solely Buster-Jangle Sugar. Largely due to the fact that the model depended upon lengthy hand calculations, it did not become widely used; and later RAND work was based upon R-265-AEC rather than Dishington's model.

Prior to the appearance of the next model to be discussed, there were some notable activities in 1955 and 1956. In January 1955, the Armed Forces Special Weapons Project (AFSWP) sponsored another fallout symposium. At this meeting the few fallout models under development were compared. They were fairly similar in their approach (stabilized cloud disk-tossers), but the results were wildly divergent - due in large part to differences in the data inferred from the test shots (Ref 18:7). In March of that year the 1 kiloton subsurface Teapot Ess shot in Nevada produced a useable fallout pattern. This test also resulted in a significant base surge, a feature to be incorporated in more advanced models years later. In March 1956, PVTM-18-56 (Ref 28) was produced by the Air Force Intelligence Center. Although not a model in the sense of mathematically modeling the fallout process, it is the earliest manual printed by the government whereby fallout prediction was reduced to a simple handbook procedure. In May and June 1956, three of the Redwing series of nuclear tests in the Pacific were surface bursts. With weapon yields of 40 kilotons (LaCrosse), 3.53 megatons (Zuni), and 12 kilotons (Seminole), these shots were relatively well documented. Together with two Buster-Jangle shots, these tests represent even now the bulk of reliable information for cloud structure and particle size/activity distributions for surface shots.

Also in June 1956, RAND published P-882-AEC, "A Mathematical Model of the Phenomenon of Radioactive Fallout (Ref 29). The model

appears to have been a refinement of the first RAND model presented in the Aureole report. It pointed to some of the items of interest in the fallout modeling business at the time: particles were assumed to fall as though they were spherical (page 6, much work was performed later by RAND and others to explore the accuracy of this assumption); drag coefficients were used to compute the particle fall rate (page 3, early attempts to use Stoke's law alone had produced unacceptable fall rates for the larger particles); the particle size/activity distribution used for the Buster-Jangle Sugar shot appeared satisfactory for the Pacific tests as well (page 3, but there remained a divergence of opinion on this subject outside of RAND); and mass in the cloud was assumed to be distributed as a decreasing exponential with increasing altitude (page 8, this assumption was apparently based upon an exponential atmospheric density). As an extension of earlier work, this paper offered few new ideas, but it did introduce the use of electronic computers in fallout prediction. The model was a mixture of computations on the IBM-701 to transport the disks and hand calculations to smooth and interpret the results.

In February 1957, the first major open-literature paper on fallout prediction was published in the Journal of Meteorology (Ref 17). Written by Kellogg, Rapp, and Greenfield, all of RAND, the paper was entitled "Close-In Fallout." The authors present some hypothetical results which were computed using a disk-tosser of 100 vertical layers and 100 particle size groups. In March 1957, RAND sponsored another fallout symposium. The models reviewed there had undergone only minor changes since the 1955 AFSWP symposium, but the participants carried away from the meeting new and more consistent test shot data to input to the next generation of fallout models (Ref 20:7).

In November 1957, the armed forces issued a new weapons effects manual (Ref 6). The Army's version was TM 23-200. Like PVTM-18-56, the residual radiation material in TM 23-200 was not a true model, but a simplified handbook prediction system. Also as with the PVTM, it was based primarily upon the dose rate contour area coverage of actual test shots. However, since the test data available at the time the manual was being written was somewhat sparce, the current RAND model computer code was used to fill the gaps (Ref 11).

In February 1958, RAND issued another paper, RM 2115, "A New Model for Fallout Calculations" (Ref 30). A disk-tosser computer program, the model presented by RM 2115 was commonly referred to as the second RAND model. It introduced several refinements over P-882-AEC including wafers having a horizontal distribution of activity that tapered off at the edges (possibly in an attempt to reduce the need for smoothing the results) and the capability to vary some of the input parameters such as the particle size/activity distribution. Indeed, a stated purpose of the model was to investigate the effects of varying these parameters in the hope of finding a set that yielded optimum results. The model also used, for the first time, an explicitly log-normal distribution of activity with particle size - a type of function that would become the standard.

In June 1958, yet another new RAND model was described in RM 2193, "A Simplified Model for Fallout Calculations" (Ref 31). After its experiences with the disk-tosser programs, codes requiring a great deal of computer time, RAND began to search for methods to simplify the calculations of particle transport. By manipulating equations, performing empirical fits, and making some simplifying

assumptions, a set of equations that could be solved by hand were sought. Such a set was arrived at, but the authors of the report decided that the solution was so difficult to obtain that whatever might have been gained relative to the unwieldy computer programs was more than offset by the loss of a clear mathematical description of the physical processes of fallout. Although even the authors admitted that the paper was somewhat of a dead end, the paper was the beginning of a transition at RAND.

One of the assumptions used in RM 2193 was a homogeneous cloud. This allowed the cloud to be transported not just as individual wafers but more as a unit to be "smeared" on the ground. It thus became useful to talk in terms of the fraction of the cloud arriving at a point on the ground, and the irregularities of the disk-tosser were replaced by smooth contours. This transition would be completed at RAND with its next report, and the concept would be adopted by at least one other group.

In January 1959, however, a model was presented that no only did not follow this trend to "smearing" the cloud, but went the other direction to introduce a new class of model that sought to describe the fallout process in greater detail. The Naval Radiological Defense Laboratory's "D" model, described by Anderson in USNRDL-TR-289 (Ref 2), abandoned the stabilized cloud (typically assumed to be present 5 to 10 minutes after the burst) and attempted to model a dynamic cloud from its formation within seconds following the burst, through its rise, to its eventual deposition on the ground. The methodology was essentially to allow cloud rise and particle fall to occur simultaneously; none of the actual particle formation processes to appear years later were present in the D model. At the time of its inception, NRDL-D, a disk-tosser, was probably the most sophisticated fallout model

running. Although it apparently did not directly evolve further, this model was significant because it led the way for others to follow.

The model described in WSEG-RM-10 of October 1959 (Ref 27), was a model that did adopt the practice of "smearing" the cloud. The model assumed a single effective wind and, with some accounting for shear, deposited activity as the cloud moved downwind. The methodology is in many respects very elegant and straightforward; but, as Russell has pointed out (Ref 35:208), the key to WSEG-10 lies in the function g(t).

The function g(t) is the fractional rate of activity deposition from the cloud to the ground at time t. (The time integral of this function is then the fraction of the cloud activity that has landed by time t.) The same function, though under a different name ($\Psi'(t)$), also appears in the third RAND model presented in RM2460 of February 1960 (Ref 4).

Conceptually, WSEG-10 and RM2460 are strikingly similar, but the mathematical details vary considerably. The authors of WSEG-10 were fully aware of the work at RAND on RM2460. Indeed, some of the data in WSEG-10 and the concept of the g(t) function appear to have originated at RAND (Ref 32 and 33). But the two models arrive at g(t) in an entirely different fashion.

In RM2460, g(t) is computed as part of the basic program based upon original cloud height and particle fall velocities. Consistent with RAND's own analysis of test shot data, g(t) versus t plots looked similar to a log normal distribution function - although RAND never assigned to it a single functional type. (At the 1962 fallout symposium, though, J. W. Reed of the Sandia Corporation stated that workers on the Sandia prediction system had decided some years previous to the symposium that the activity fall rate was, indeed, log-normal (Ref 18:145).

In WSEG-10, however, g(t) is flatly assigned essentially a negative time-exponential form. It appears as though this form for g(t) was an empirical fit to the RAND data, but this fit would necessarily be very poor at very early times. If the authors recognized this error, no mention is made of it in WSEG-RM-10. Quite the contrary, the source of g(t) is a complete mystery - a shortcoming for which WSEG-10 has been criticized. (It should be mentioned here that the document used by this author, and apparently by others, to evaluate the "WSEG-10" model was WSEG-RM-10 itself. M. Polan of the Ford Instrument Company, in his September 1966 document comparing various fallout models (Ref 26:31), points out that the WSEG model, as it had evolved by 1962, differed significantly from the form in which it was published. Unfortunately, Polan did not elaborate on the issue.)

Both the RM2460 and WSEG-10 models suffered from a loss of physical detail by "smearing" the cloud in order to avoid disk-tossing. Consequently, they failed to yield accurate patterns for highly sheared winds. But the advantages they had to offer were tremendous; they yielded useful, clear fallout patterns with a minimum of effort and with the expenditure of much less computer time.

The RM2460 model was later incorporated into a computerized system by RAND, called Quick Count, to estimate strategic casualties due to combined nuclear weapons effects (Ref 39). But for some reason neither Quick Count nor the basic RM2460 model attained widespread use; so this model represents, in effect, the last of the RAND work on fallout. WSEG-10, on the other hand, was nearly immediately adopted for use by the National Resource Evaluation Center (Ref 18:49). The model attained a popularity and, through the SIDAC system, continues in use to the present day.

In September 1961, the U.S.S.R. unilaterally resumed an ambitious schedule of atmospheric nuclear testing, thereby breaking a moratorium on such testing observed since November 1958. In September 1962, a major fallout symposium was sponsored by NRDL and the Defense Atomic Support Agency (DASA, successor to AFSWP), which marked the beginning of a new era in fallout modeling.

IV. Chronology: 1962-1979

With the resumption of atmospheric testing, seven shots in the Nougat and Storax series in 1962 resulted in local fallout patterns. Most of these, however, resulted from relatively low yield subsurface bursts and were therefore limited in extent. Even with the moratorium on testing ended and an ambitious pace of test detonations underway, it was apparent to the scientists working on fallout modeling that the chances of ever again conducting a test resulting in a large amount of fallout were extremely dim. With this knowledge, another fallout symposium was held at the Naval Radiological Defense Laboratory in September 1962.

At the symposium, 17 systems for predicting various aspects of fallout were presented (Ref 18:16-17). Among them were the Army's field system, a "modified" version of WSEG-10, the third RAND model, and the USNRDL-D model. The predictions systems were classed as true models, systems that mathematically modeled aspects of the fallout process (often only particle transport), or as systems that answered more limited, specific questions (such as where the pattern would lie or how large certain isodose contour areas would be) by using methods of comparison to test data. These latter systems, taking essentially a

handbook approach, were of great interest to the military services for field use; but the true models were of most interest to the symposium. These were further subclassed depending on whether the model was a disk-tosser or one that "smeared" the cloud (i.e., one that did not divide the cloud into wafers).

In contrast to the 1957 symposium, the models presented in 1962 gave reasonably consistent results with each other and generally with the test shots. This agreement reflected a consensus among the participants that atmospheric transport of the fallout particles was becoming fairly well understood. They concluded that the emphasis in modeling research should thereafter shift to earlier times in the fallout process; e.g., cloud formation and fractionation. Of the fully working models presented, only the NRDL-D model attempted to model cloud rise. But work near completion by Miller and work recently underway by DASA on a new comprehensive model had already entered these new areas and will be noted below.

Reports on the symposium and analyses and comparisons of the models presented there took no less than six years. Although NRDL's final report on the symposium was not published until November 1965 (Ref 18), Russell (Ref 35) had written the first comparative critique of three of the important models: WSEG-10, NRDL-D, and Quick Count deriving its fallout model from RM2460.

Russell's comments on the normalization and surface roughness factors used by the models would be repeated later by others in more detail, and he did little to actually describe the merits of the three models relative to one another. But he did conclude that the particle size/activity distributions were incorrect and certainly oversimplified.

He argued that the distributions assigned too great a fraction of the activity to the larger particles and thereby overestimated local fallout doses by as much as a factor of five (Ref 35:197). His own view was that the relationship between size and activity was a very complicated one. His recommendations were to develop methods to model the thermodynamic processes in the cloud to determine the manner in which individual nuclides form in particles and to reexamine extensively the actual fallout debris collected from the weapons tests. His latter recommendation was apparently not enthusiastically acted upon; certainly it would have been a tremendous undertaking. The first recommendation was already being implemented by Miller and DASA.

Russell also made a comment that brings to the fore a major point of the fallout modeling game. This is that the best prediction methods toy with uncertainties that quite easily result in a factor of two variance in the dose for a given case. The response of the human body to radiation, however, not being in any sense linear, may amplify an error to result in a factor of 20 to 100 variance in casualties. Thus, in the cases where these models were used for strategic studies, a fine tuning of the significant digits in one of the multiplicative constants in a model was reflected in the loss or gain of many thousands of lives (Ref 35:45).

This concern over multiplicative constants (in particular normalization and surface roughness) was also evident in comments made in the aftermath of the 1962 symposium by Mackin and Mikhail in December 1965 (Ref 22), by Polan in September 1966 (Ref 26), and by Seery in November 1968 (Ref 36). Polan's work in particular shows an unexpectedly wide variation in the particle size/activity distributions used by the various 1962 models considering that the distributions typically owed

their origins to the single Buster-Jangle Sugar shot. Perhaps in response to the scientists' complaints that the actual data from test shots were difficult to compile in order to analyse a fallout model, the DASA 1251 series of volumes on Local Fallout From Nuclear Test Detonations was issued in the mid-1960's (Ref 19).

The first new model to appear after the 1962 symposium, one proposed in a series of works by Carl Miller (Ref 24) and sponsored by the Office of Civil Defense, was also the first to attempt modeling the radioactive cloud thermodynamically and to attempt modeling fractionation. At the time of its appearance in 1963, it was described as the "state of the art" (Ref 22:10); but perhaps due to its difficult reading, the Miller model soon yielded the limelight to the new DASA model.

This model, a computer code named DELFIC, was intended to be very comprehensive and to be used only as a research tool rather than for operational use. Completed in 1966, the code ambitiously sought to model the entire fallout process using as much as possible first principle physics rather than empirical information. In terms of transport it was a disk-tosser; but it examined areas (such as soil composition, fractionation, individual radionuclide decay, and vertical winds) that pre-1962 codes had entirely ignored. It was in 1966, and remains today (after some modification), the last word in fallout models. But it has earned its standard-setting reputation at the expense of being rather intractable.

Because the code can be very expensive to run and extremely difficult to learn how to run, the work done since 1966 on fallout models other than DELFIC has been to develop models that approach DELFIC's capabilities without its difficulties. The models of most interest are PROFET (developed in 1969 for Army field use), SEER (appearing in at

least three versions, the second appeared in 1972 as SEER II), KDFOC (1972), AUGER (a follow-on to KDFOC developed in 1975), and LASEER (a 1975 rewrite of SEER by the Los Alamos Scientific Laboratory). The models are in some cases (PROFET, SEER, and LASEER) direct derivatives of DELFIC; and in terms of particle transport, all are essentially disk-tossers. So whereas the differences between the 1962 models were most often expressed in terms of their transport methodology, the differences between the members of the current generation of models lie mainly in the compromises that are made to simplify the models relative to DELFIC.

The features that would be mentioned in a comparative analysis of the models would include map preparation, presentation of results, methods of smooting the results (from the traditional disk-tosser), cratering calculations, induced activity, subsurface burst capability, stem modeling, fractionation, turbulence, cloud rise, throwout, strongly sheared winds, vertical winds, ability to account for sail composition, height of burst adjustments, length of computations, computer core required, case of usage, amount of input data required, and (still) normalization factors. The scope of this paper precludes a comparison of these models, particularly as most of them have evolved through several variations. Norment (Ref 25) has attempted such a comparison, and his paper is highly recommended to the interested reader.

V. Histories of Specific Handbook Prediction Systems DNA EM-1, Capabilities of Nuclear Weapons

The Defense Nuclear Agency's effects manual EM-1 (Ref 10) is very widely used within the Department of Defense to evaluate nuclear weapons effects, only one of which is fallout. Its effective predecessor was TM 23-200 (Ref 38), described above in Section III.

TM 23-200 was very widely used in the late 1950's and early 1960's and played the same functional role as a manual for evaluating weapons effects as does EM-1 now. The manual was revised in 1962; but the revisions were not of major proportions, possibly because the feverish pace of weapons testing (following the end of the moratorium begun in 1958) left little manpower to write the revisions or evaluate the latest test data. In 1969, though, the Defense Atomic Support Agency (successor to AFSWP and predecessor to DNA) was instructed to completely rewrite the effects manual. The end result of this effort was the current version of DNA EM-1 (Ref 11).[2]

EM-1 has two major sections on fallout prediction: one covers bursts over dry land, and the other treats bursts over or under water. The information on water bursts is presented as an extensive set of dose rate contours for various burst conditions. These contours were generated by a computer code named DAEDALUS (Ref 10:V-107) developed by the Naval Radiological Defense Laboratory. The code is apparently no longer used (Ref 11).

The land burst fallout information is presented as idealized H+1 hour dose rate contours, where the contour parameters (dose rate, downwind distance, maximum crosswind width, downwind distance to maximum

[2] The detailed transition from TM 23-200 to the current DNA EM-1 dated 1 July 1972 (Ref 10) is not well understood by the author. The authentication page forwarding DNA EM-1 (1972) states that it supercedes DASA EM-1 dated January 1968 (redesignated DNA EM-1 in July 1971, upon the organization of DNA). Furthermore, it is stated that whatever effects manual was in effect prior to the date, it was redesignated DASA EM-1 on 8 July 1966. Precisely where these other versions of "EM-1" originated, how they were related to TM 23-200, or what the forerunner of DASA EM-1 of July 1966 was, is unknown. However, it is known that DASA EM-1 was significantly different in its structure and content than the current DNA EM-1 (Ref 6).

width, and ground zero diameter) are presented as a function of yield in a family of graphs for various effective wind velocities. As stated in the manual (Ref 10:V-72), the contours were generated by the computer code DEFIC using a 15° effective shear. However, further inquiry into the source of these contours has yielded a more complete picture than that given in the manual.

DELFIC, generally regarded as the most reliable fallout prediction model available, was the primary, but not the sole, generator of the idealized contours presented in EM-1. The precise data concerning weather and burst conditions input to the code are, however, no longer available. Particularly, the wind velocity variation with altitude used by the authors of EM-1 to produce the ultimate effective wind with 15° shear has apparently been lost. Therefore, any attempt to confirm the origin of the contours by directly comparing them with results of a DELFIC run would be very difficult and subject to a significant degree of doubt. Moreover, according to the author of EM-1 DELFIC was not the sole source of the information yielding the contours (Ref 11).

Due to the cost involved in running the large DELFIC code, extensive use was also made of the SEER code (Ref 20). Although comparisons of the results from SEER and DELFIC were made to insure consistent data for construction of the contours, the use of the SEER code introduces an additional obstacle in any attempt to reproduce the contours (Ref 11).

Effects of Nuclear Weapons (1977 edition)

The 1977 edition of Effects of Nuclear Weapons (Ref 15) is the latest link in a chain of books originating with Effects of Atomic Weapons published in 1950. Unclassified and published by the government, the books have been easily available and widely used.

The information in Effects of Nuclear Weapons (ENW) is directly attributable to the contour parameter graphs presented in DNA EM-1. However, the information in ENW has been reduced from the series of graphs to a short set of yield-dependent equations giving the contour parameters (downwind distance, maximum width and ground zero width for eight dose rates at H+1 hour) with scaling laws used for variations in yield and effective wind speed. Through EM-1, then, the real roots of the scheme lie in DELFIC and SEER (as explained above) (Ref 11).

Although, as pointed out earlier, it would be extremely difficult to directly compare ENW predictions to DELFIC results, direct comparison of results from ENW to those from EM-1 is a simple matter. Such a comparison has shown the two methods to agree remarkably well considering the differing approach to calculation of the contour parameters.

The Army Fallout Prediction System (FM 3-22)

The Army fallout prediction system is a scheme developed in 1957 or 1958 to serve the Army's needs in the field. Its purpose was not to truly model the fallout phenomenon, but to predict with a high degree of confidence an area within which the actual fallout pattern would appear. The object was not to predict the precise location of the actual dose rate contours, but to define a larger area within which field measurements would determine the dose rate information to be used for tactical decisions.

The system was very simple and designed to be performed entirely by hand. In essence, the prediction consisted of constructing a fan of 40 degree angular spread, the apex centered at ground zero, opening downwind, with the downwind extent of two hazard zones determined from

nomographs. It was estimated that the fan (somewhat more complicated than described here) would contain the dose rate contours of interest (100 rads accumulated by exposed personnel within the first four hours following the arrival of fallout, and 20 rads within six hours) with a 93% probability for bursts occurring up to two hours after the meteorological readings used to determine the effective wind vectors were taken. Furthermore, the system seemed to perform well for all the test shots conducted by 1962 (Ref 18:103-107).

The Army system could basically only serve as a warning to trigger radiological monitoring within the pattern and serve as a relatively reliable means of defining areas outside the pattern that would not receive militarily significant fallout. On the other hand, the system offered great advantages in its simplicity and the reliability attained through its very conservative approach. Clearly, a fallout model which more precisely predicted fallout patterns might have been desirable, but the Army decided against such a model for several reaons. First, at the time that the Army's sytem was developed, no model was deemed to be accurate enough to justify basing tactical decisions on its predictions (Ref 11). Secondly, the capability to use the more sophisticated systems in the field, dependent upon possessing highly trained specialists and a large machine computation capability, was not present. And third, the capability to determine the actual burst conditions of an enemy strike was very limited.

The accuracy of any fallout model is strongly dependent upon an accurate knowledge of the burst conditions. The meteorological information is generated regularly by the forces in the field (although in less detail than the most sophisticated models are capable of

handling), and the ground zero may be accurately located by common map techniques. However, the weapon yield, weapon design, and height of burst are not easily determined in the field. Although development of a device to accurately measure these variables was proposed, no such equipment was in fact fielded.

Despite the lack of sophistication of this prediction system, it has, more so than any fallout model, withstood the tests of time and widespread use. It was adopted by the Marine Corps and accepted by NATO as its standard prediction system. From the Army's TC 101-1, through TM 3-210, to the current FM 3-22 (Ref 12), the system has remained in constant use - its form virtually unaltered.

PROFET (a derivative of the DELFIC code) was developed in 1969 for possible use in the field. Again, however, the lack of reliably accurate results, computer capacity in the field, and poorly defined burst conditions prevented the adoption of this model. So although PROFET is still in the Army's inventory of available codes, it is no longer actively used (Ref 21 & 23). The most significant change in the manner in which the Army predicts fallout since the late 1950's will thus be the programming of the old system in the automated TACFIRE fire control computer in the near future (Ref 21).

<u>Physical Vulnerability Handbook - Nuclear Weapons</u>

AP-550-1-2-69-INT, the Defense Intelligence Agency's (DIA) <u>Physical Vulnerability Handbook - Nuclear Weapons</u> (Ref 3), being a handbook for nuclear weapons effects vulnerability, presents a fallout prediction system utilizing idealized contours. The roots of this system are traced carefully in a paper by Charles R. Thomas (Ref 37); a brief summary of this information is given below.

The document providing the bulk of the fallout material still present in the handbook was PVTM-18-56, "Effectiveness of Radiological Fall-Out as an Area Denial Agent," published in March 1956 by the physical vulnerability section of the Air Force Intelligence Center (Ref 28). PVTM-18-56 gave rise in May 1958 to the Air Force manual AFM 200-8, "Nuclear Weapons Employment Handbook" (Ref 1). (A copy of neither document was found by this author, so little is known of the material they present. Note, however, that PVTM-18-56 preceded AFM 136-1, the Air Force's equivalent to TM 23-200, by more than a year; and AFM 200-8 was published about eight months after AFM 136-1). AFM 200-8 gave rise in September 1963 to the newly created DIA's PC 550/1-2, "Physical Vulnerability Handbook - Nuclear Weapons," the direct predecessor of the current handbook.

In addition, from 1956 to the present, the material in these documents has been under constant, but usually minor, revision. DASA EM-1 (January 1968) and WSEG-RM-10 are two documents which have contributed to these revisions. The paper by Thomas traces these revisions in detail.

VI. Conclusions

The evolution of fallout modeling can be quite briefly summarized. The very early models were stabilized cloud disk-tossers using hand computations. Through the mid-fifties, the disk-tosser model was improved with the availability of better data and the use of machine computations. In the late fifties, some effort was spent to decrease the cumbersomeness of the computationally lengthy disk-tosser models by "smearing" the cloud. Around 1960, a shift to modeling a dynamic cloud was seen. In the early sixties work began to develop a com-

prehensive code modeling the cloud in a complex thermodynamic fashion; the result of this effort is typified by the DELFIC code. Since then, efforts have been either to make slight improvements to DELFIC or to write codes simpler than it without sacrificing much prediction capability. And concurrent with the evolution of the fallout models of some complexity has been the evolution of an array of fallout prediction systems not afforded the title "model."

After these nearly 30 years, three basic types of fallout prediction systems remain in use. Although they differ greatly these three types have survived because they have one thing in common: they fill a need. The first type is the handbook system, typified by DNA EM-1, the DIA handbook, and FM 3-22. Although the least capable of the three system types, the handbooks offer two major advantages: one needs relatively little training and virtually no special equipment to use them, and the input data on burst conditions are minimal. Most probably, no significant improvements in these simple systems will be realized in the near future.

The second type of prediction system that has stood the test of time is the WSEG-10 model, itself. Unlike the handbook systems, the WSEG-10 model requires a digital computer; but its advantage lies in its great simplicity and ease of computation relative to the third system type. The WSEG type of model does offer, however, fertile ground for improvement, as evidenced by two recent papers proposing specific changes (Ref 5 and 34).

The third system type, consisting of DELFIC and its close relatives, offers the "best" fallout prediction capability available; but they do so at an expense of computation time. As this model type is still under development, improvements are to be expected.

The science of fallout modeling, born in the wake of the first themonuclear detonations in the Pacific, has evolved from a hand calculational model in the report on Project Aureole to the current large computer codes. Yet despite the tremendous increase in sophistication, many features of fallout prediction methods in use today reflect events or innovations of two decades or more ago.

Most obviously, the data base relies almost entirely on some of the earliest nuclear test shots. Beyond this, the WSEG model developed in 1959 is still in use, and the Army's system described in FM 3-22 is exactly the system used in 1958, to name only two of the older prediction systems still in use. But even DELFIC owes the basic disk-tossing technique of particle transport to the very first models, so in a small sense the evolution has come full circle.

But many questions are as yet unanswered. For instance none of the codes attempt to model the complex wind patterns that exist at low altitudes over real terrain features and that affect the final descent of a fallout particle. This final perturbation is nonetheless important because it causes the hot spots and unexpectedly clear areas that characterize real fallout patterns but are absent from calculational models. Whether such questions will ever be adequately answered, whether they are answerable with the test data available, or, simply, what direction future efforts in fallout modeling will be in are questions themselves yet to be answered.

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The development of the science of fallout prediction in this country from 1950 to 1979 is described. The chronological description emphasizes early developments and the relationships between some of the significant calculational models. The earliest work on fallout prediction discussed is that performed by RAND on Project Aureole in 1954, and the evolution is carried through to the derivatives of the DELFIC computer code. A section is devoted to the histories of four commonly used handbook prediction systems.

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